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The histology of epiphyseal union in mammals

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INTRODUCTION

Epiphyseal union may be defined as beginning with the completion of the first mineralized bridge between epiphyseal and diaphyseal bone and ending with the complete disappearance of the cartilaginous epiphyseal plate and its replacement by bone and marrow. The phases have been described by Sidhom & Derry (1931) and many others from radiographs, but histological material showing union in progress is rare, probably because of the rapidity with which union, once begun, comes to completion (Stephenson, 1924; Dawson, 1929).

Dawson (1925, 1929) described the histology of 'lapsed union' in rats, where the larger epiphyses at the 'growing ends' of the long bones remain un-united throughout life. He and Becks *et al.* (1948) also discussed the early and complete type of union found at the distal end of the humerus in the rat. Here a single narrow perforation pierced the cartilaginous plate near the olecranon fossa and later spread to destroy the whole plate. Lassila (1928) described a different type of union in the metatarsus of the calf, with multiple perforations of the plate. Apart from a few notes on human material (Haines & Mohiuddin, 1960, 1968), nothing else seems to have been published on the histology of union in mammals. In this paper more abundant material from dog and man is presented and will serve as a basis for discussion of the main features of the different types of union.

MATERIALS AND METHODS

Human epiphyses were collected over many years in Lagos, Kampala and Accra. As stated ages could not be relied on, ages are not given. A few good specimens were taken from subjects prepared for dissection, but most were gathered during systematic visits to post-mortem rooms, where speed of extraction and repair of the incision were essential. So the smaller and more accessible epiphyses at the elbow are better represented than the larger ones at the shoulder and hip. These fragments, though few and often poorly fixed, are all that are available.

Each epiphysis was sawn in the fresh state, using a longitudinal cut in the widest plane. The lower end of the humerus, for example, was cut in the plane passing through the two epicondyles, the radius through the longer diameter of its head and the ulna through the coronoid and olecranon processes. The surfaces were washed very gently under running tap water, disturbing the marrow as little as possible,

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and then examined by eye and by gentle probing with a needle for areas of union. In some cases radiographs were taken either before or after fixation, but this proved time consuming and a burden to the hard worked departments concerned, while giving little additional information. Most of the specimens were rejected as being too early or too late for study of the process of union, but promising material was photographed, further trimmed and processed for histological examination.

The selected material was fixed in formol saline and decalcified, either in the country of origin or in England. Decalcification using R.D.C. (Bethlehem Instrument Co.), followed by staining with haematoxylin and eosin, gave the most satisfactory preparations. Often the cartilage showed excellent preservation and demarcation of calcification boundaries even though the marrow was in a state of decomposition (as in Fig. 29).

Good material was occasionally lost in the sawing. For example, the very limited area of union at the distal end of the tibia (Fig. 5) only appeared at one side of the sawcut and was so shallow that it was gone from the block before a good section could be made. So the photograph remains as the only record. Attempts to avoid such cutting until after decalcification proved unsatisfactory, as both fixation and decalcification were slowed. Nor could radiographs be relied on to identify material suitable for detailed investigation.

The human series was supplemented with material from 4 dogs, 3 home bred (provided through the kindness of Professor A. Mohiuddin and prepared by Mr H. L. Chan in Singapore) and a stray. These healthy, well-nourished animals provided a comparison for the possibly pathological human material and included examples of the later-uniting epiphyses not otherwise available. Some of the material has been kept in paraffin blocks for possible future study by other workers interested in union.

OBSERVATIONS

The results are more usefully given under a series of headings based on topics rather than as a catalogue of specimens.

The growth plate at the approach of union

A fresh radial head (Fig. 1) and an ulnar olecranon epiphysis (Fig. 2), known to be approaching union since they were taken from a subject in which the lower end of the humerus was already united, showed continuous, i.e. unbroken, growth plates of cartilage separating the epiphyses from the shafts. The humeral head (Fig. 3) and femoral head and great trochanter (Fig. 4) from a dissecting room subject

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Figs. 1–6. Epiphyses approaching union and in early union, before processing.

Fig. 1. Head of radius.

Fig. 2. Olecranon of ulna.

Fig. 3. Proximal end of humerus.

Fig. 4. Proximal end of femur.

Fig. 5. Distal ends of tibia and fibula, arrow to perforation.

Fig. 6. Proximal end of humerus (epiphyseal plate perforation shown in Fig. 26).

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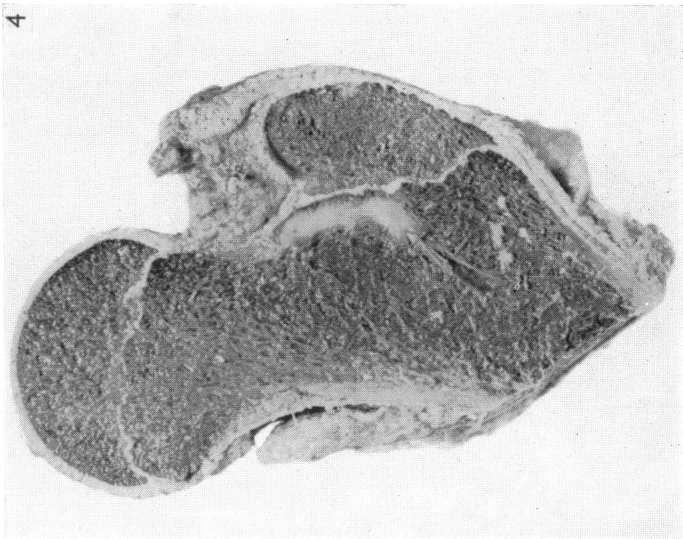

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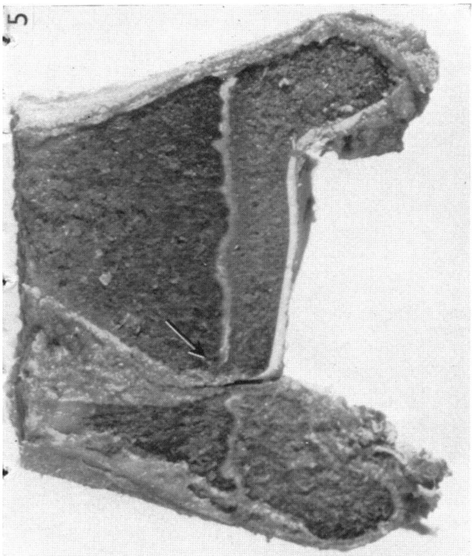

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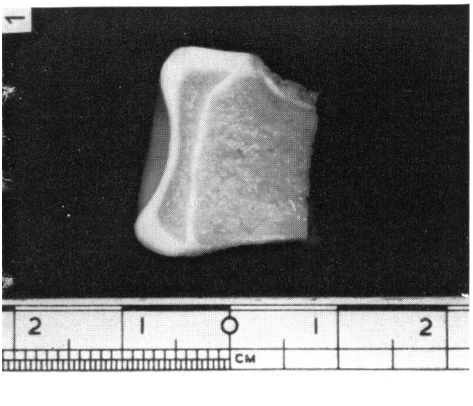

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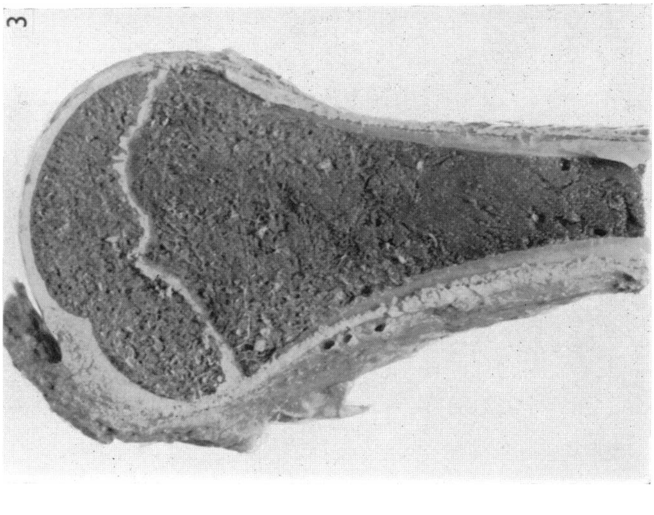

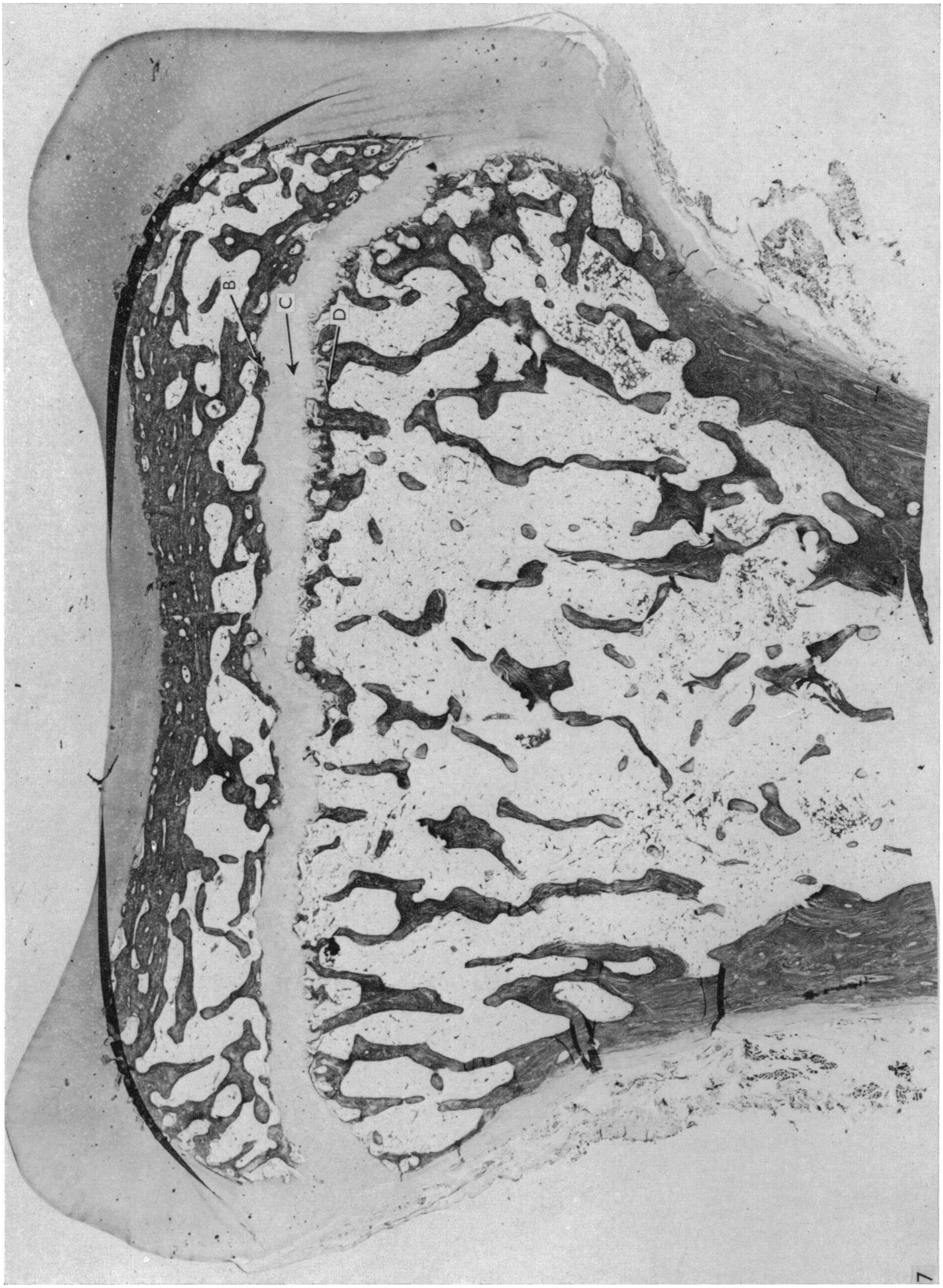

Fig. 7. Head of radius approaching union. Arrows to basal bony plate of epiphysis (*B*), cartilaginous epiphyseal plate (*C*), and diaphyseal bony plate (*D*).

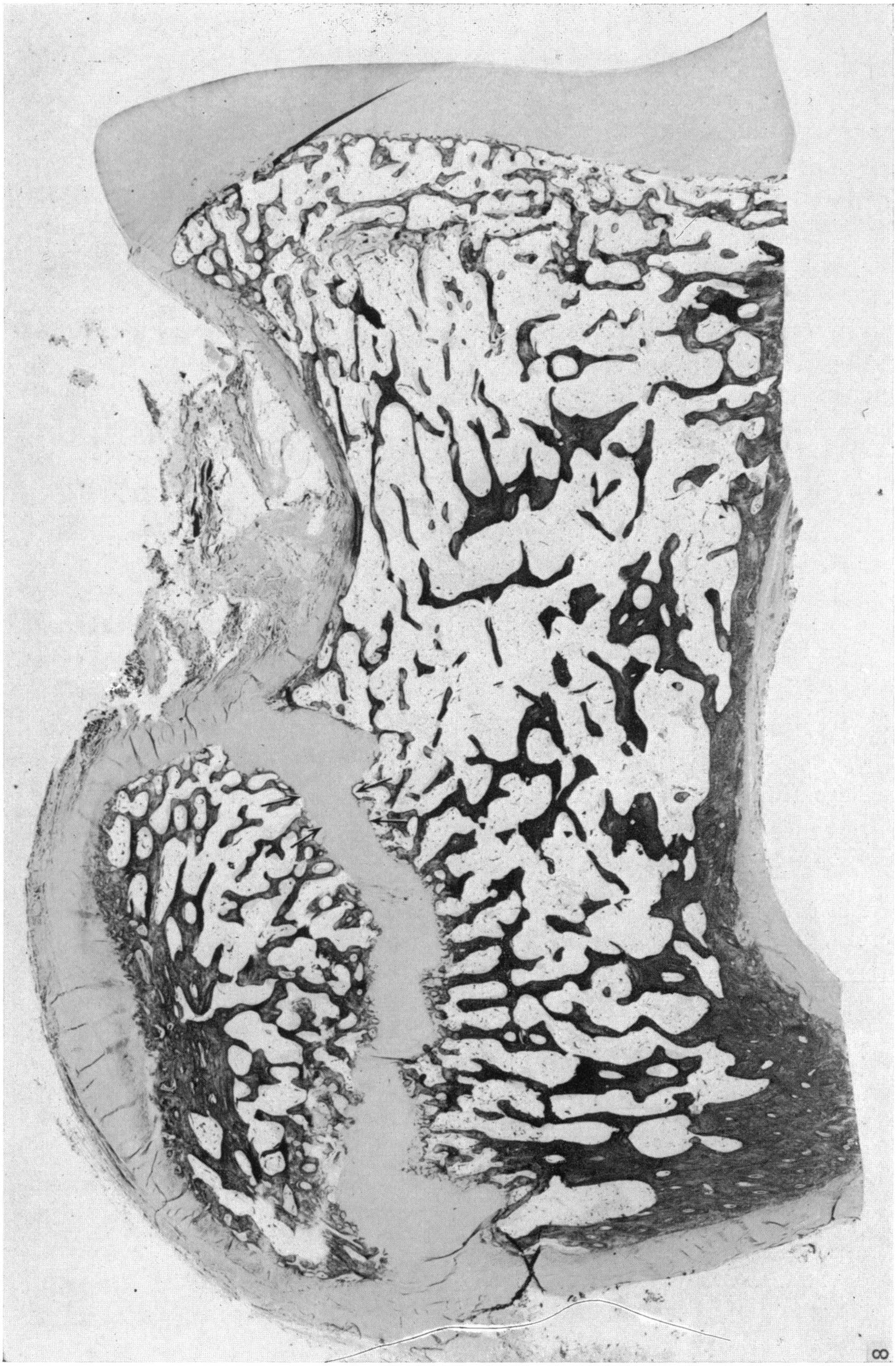

Fig. 8. Part of distal end of humerus. Medial epicondyle approaching union, trochlear region already united with no residual cartilage or bony scar. Arrows to bays of erosion on both surfaces of epiphyseal plate.

showed thinning of the cartilage, while the tibia (Fig. 5) from the same subject had a small area of union where the cartilage was perforated. A second humerus (Fig. 6), also in early union, had the cartilage further thinned.

A section of the radius (Fig. 7) showed a dense sheet of subarticular bone connected by a series of struts to a basal epiphyseal plate resting on the epiphyseal cartilage. The plate was in general relatively smooth and continuous but in some areas it was indented as if it were being invaded by epiphyseal marrow. The diaphyseal plate was more irregular and the cartilage more exposed to the marrow, with numerous bays suggesting active erosion. A similar section of the medial epicondyle (Fig. 8) showed numerous bays on both surfaces of the cartilage.

Recruitment of cartilage from the epiphyseal marrow

A plate from a young and still growing dog (Fig. 9) had well-developed cartilage columns, but inactive, reserved cartilage cells that could form new columns were relatively scarce. Between the marrow of the epiphysis and the cartilage of the plate there was a nodule of cartilage with relatively small, closely packed cells. A larger cartilage nodule (Fig. 10) from an un-united human femur was similarly situated, its deeply stained matrix contrasting with the paler matrix of the plate. The transition between the loose tissue of the epiphyseal marrow, the denser fibrous tissue near the nodule, and the cartilage of the nodule itself suggested a new formation of cartilage from the marrow. In the medial epicondyle of the humerus the basal plate of the epiphysis was poorly developed, so that relatively large areas of the cartilage were exposed to the marrow (Fig. 11). In such areas the marrow passed gradually into a layer of cartilage with flattened cells and this, with no sharp boundary, into the epiphyseal cartilage. But another medial epicondyle (Fig. 12) showed, in an area where the epiphyseal bone was better developed, a nodular formation with vascular marrow passing into a dense and poorly vascularized fibrous tissue and this into cartilage without sharp boundaries.

The new cartilage could blend with the old and so lose its identity, but, alternatively, could form populations of small cells that could be followed through the greater part of the cartilage (Fig. 13). Eventually they were lost as they took part in column formation. The matrix between these small cells often appeared fibrous, and such fibrous cartilage could be calcified with conspicuous tide-lines

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Figs. 9–14. Neocartilage formation from epiphyseal marrow.

Fig. 9. Proximal end of femur, dog of 233 days. Arrows to nodule of neocartilage. H. & E. × 62.

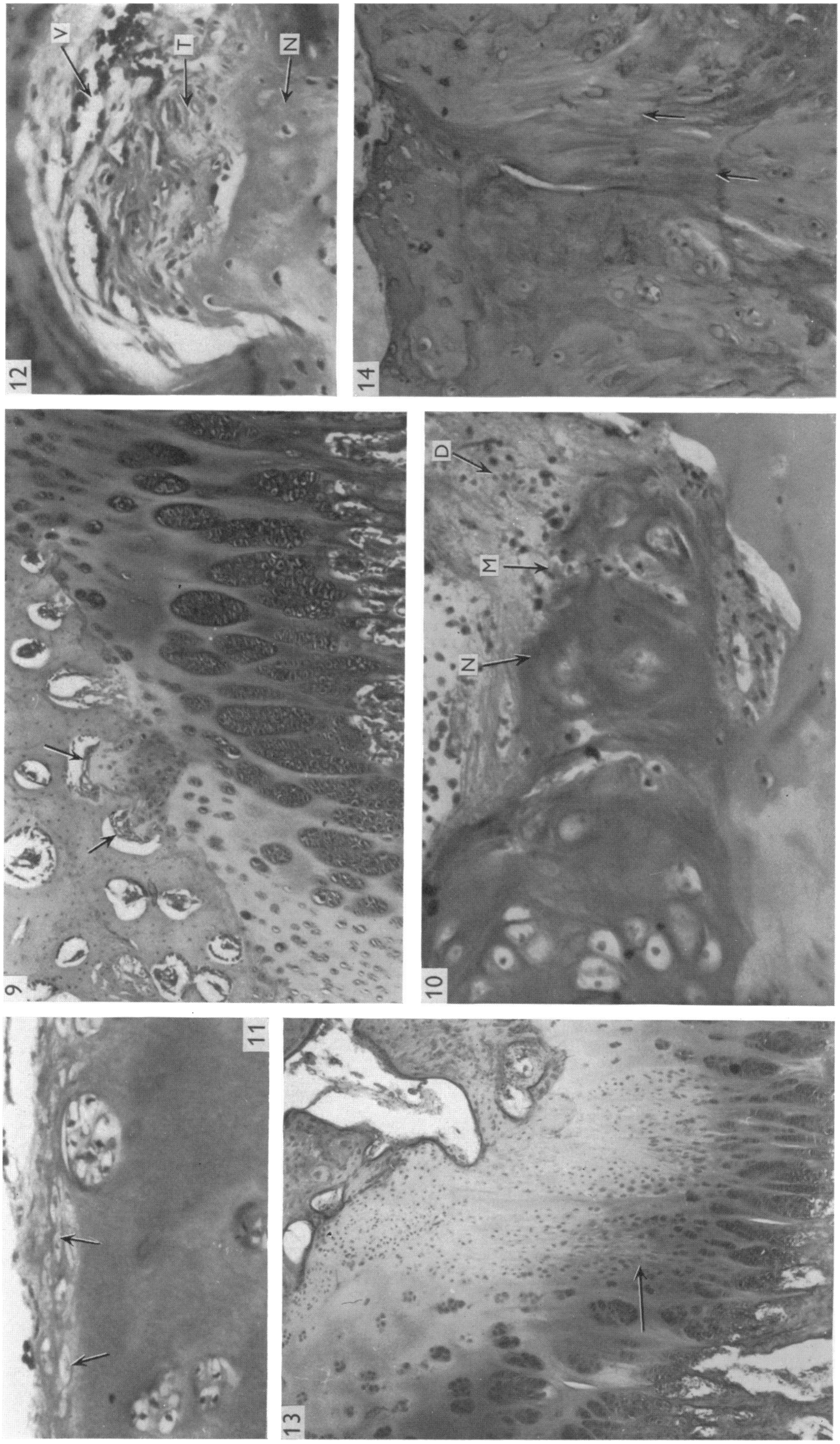
Fig. 10. Part of large nodule of neocartilage, un-united human femoral condyle. Arrows to dense marrow (*D*), mixed tissue (*M*) and neocartilage (*N*). H. & E. × 220.

Fig. 11. Medial epicondyle of humerus in early union. Arrows to flattened cells of neocartilage. Heidenhain's Azan. × 220.

Fig. 12. Medial epicondyle of humerus in early union. Arrows to vascular epiphyseal marrow (*V*), transitional tissue (*T*) and neocartilage (*N*). Heidenhain's Azan. × 175.

Fig. 13. Head of humerus in early union, as Fig. 6. Arrow to neocartilage entering zone of cartilage columns. H. & E. × 43.

Fig. 14. Material as Fig. 10. Arrows to tide-lines indicating mineralization of fibrous neocartilage. × 142.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(Fig. 14). New cartilage and the disturbances due to its presence were found in all epiphyses examined as they approached union, as well as in early union. But this was less conspicuous in the smaller epiphyses of the radius and ulna and always stopped before union was complete.

Mineralization in the epiphyseal plate

The cellular arrangement in the plate was not greatly changed at the time of union, and even the basophilic network of the matrix could be preserved (Fig. 15). But, particuarly next to the basal bony plate of the epiphysis, the cartilage was mineralized as indicated by the often multiple tide-lines, and a sharp change in texture where the mineralized met the hyaline matrix (Fig. 16). A reticulin stain brought out, very sharply, the contrast between the lamellar bone of the epiphyses, the mineralized tissue and the still hyaline region of the cartilage (Fig. 17).

On the diaphyseal surface of the cartilage mineralization was also evident, with successive tide-lines advancing amongst the cartilage columns (Fig. 18). In the glenoid fossa the tide-lines were as well developed in the zone of cartilage columns as they were on the epiphyseal surface of the cartilage (Fig. 19). In a humerus in early union (Fig. 20) the cartilage, from its cellular arrangement, might appear to be still actively growing, but tide-lines showed the columns to be embedded in calcified matrix (Fig. 21).

Early union

Perforations of the epiphyseal plates of the distal end of the tibia, olecranon, humeral epicondyle, calcaneum and radial head all appeared single and all were placed peripherally (or at least eccentrically) in the plates (Figs. 22–25). One radial head was searched through the block, but no second perforation was found. Only in a humerus (Fig. 26) did a central perforation appear, but the size of this specimen prevented a thorough search and others may have been missed.

Perforations were filled with marrow uniting the marrows of the epiphysis and shaft (Figs. 27, 28). The margins of the perforations were more or less completely lined with bone (capping plates) which covered the eroded margins of the cartilage

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Figs. 15–21. Mineralization of cartilage matrix. All epiphyses in early union.

Fig. 15. Head of radius. Arrows on left to epiphyseal lamellar bone (*L*), mineralized cartilage (*M*), basophilic network (*B*) and diaphyseal bone (*D*); on right to tide-lines. H. & E. ×57.

Fig. 16. Medial epicondyle of humerus. Arrows to boundaries of epiphyseal bone (*E*), mineralized cartilage next to epiphysis (*M*), hyaline cartilage (*H*), mineralized cartilage next to diaphysis (*D*) and diaphyseal bone (*B*). Heidenhain's Azan. ×43.

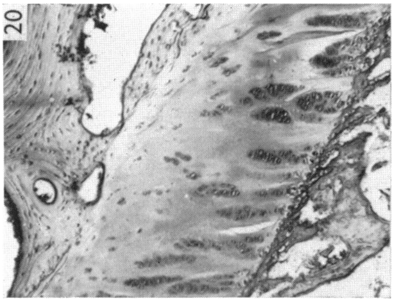
Fig. 17. Head of radius. Arrows to junction of epiphyseal bone and mineralized cartilage (*J*) and two tide-lines (*T*). Gordon & Sweet's reticulin stain. ×154.

Fig. 18. As Fig. 17. Arrows to tide-lines in zone of cartilage columns. H. & E. ×135.

Fig. 19. Glenoid of scapula. Arrows to tide-lines at both surfaces of cartilaginous plate. H. & E. ×150.

Fig. 20. Humerus, whole thickness of cartilaginous plate. H. & E. ×38.

Fig. 21. As Fig. 20. Arrows to tide-lines in zone of columns. ×135.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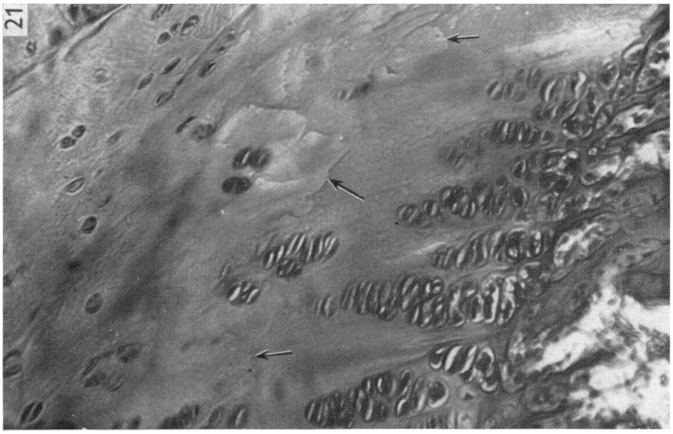
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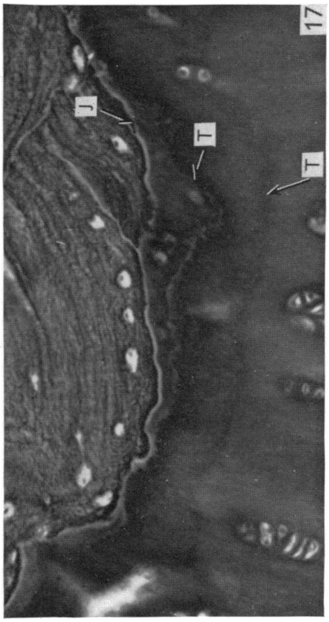
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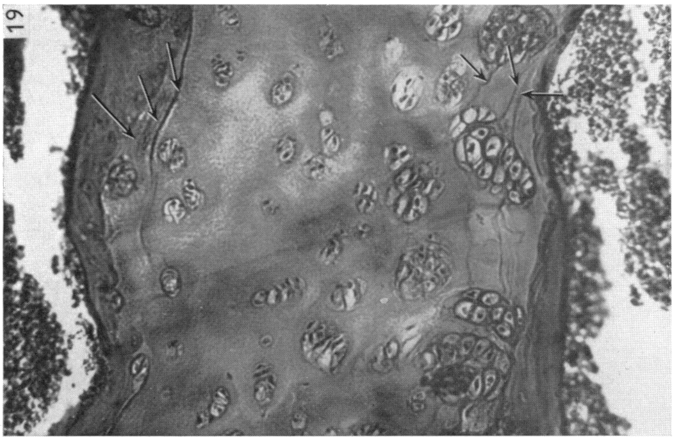
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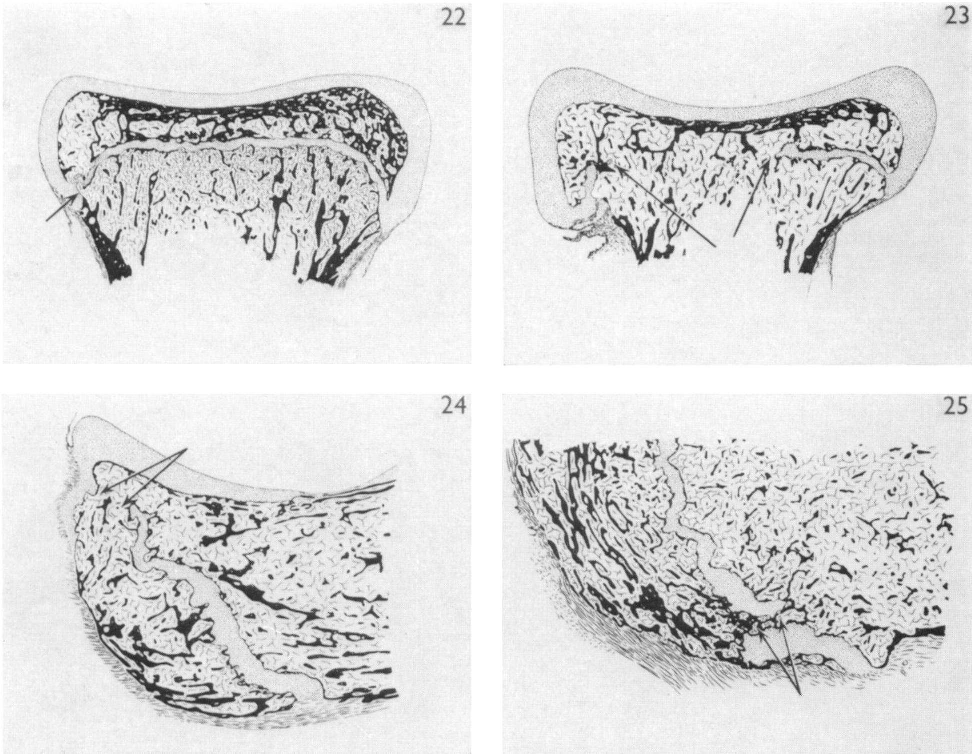


Figs. 22–25. Epiphyses in early and advancing union. Arrows to perforations.

Fig. 22. Head of radius in early union. Detail in Fig. 27.

Fig. 23. Half-united radial head.

Fig. 24. Olecranon of ulna in early union. Detail in Fig. 29.

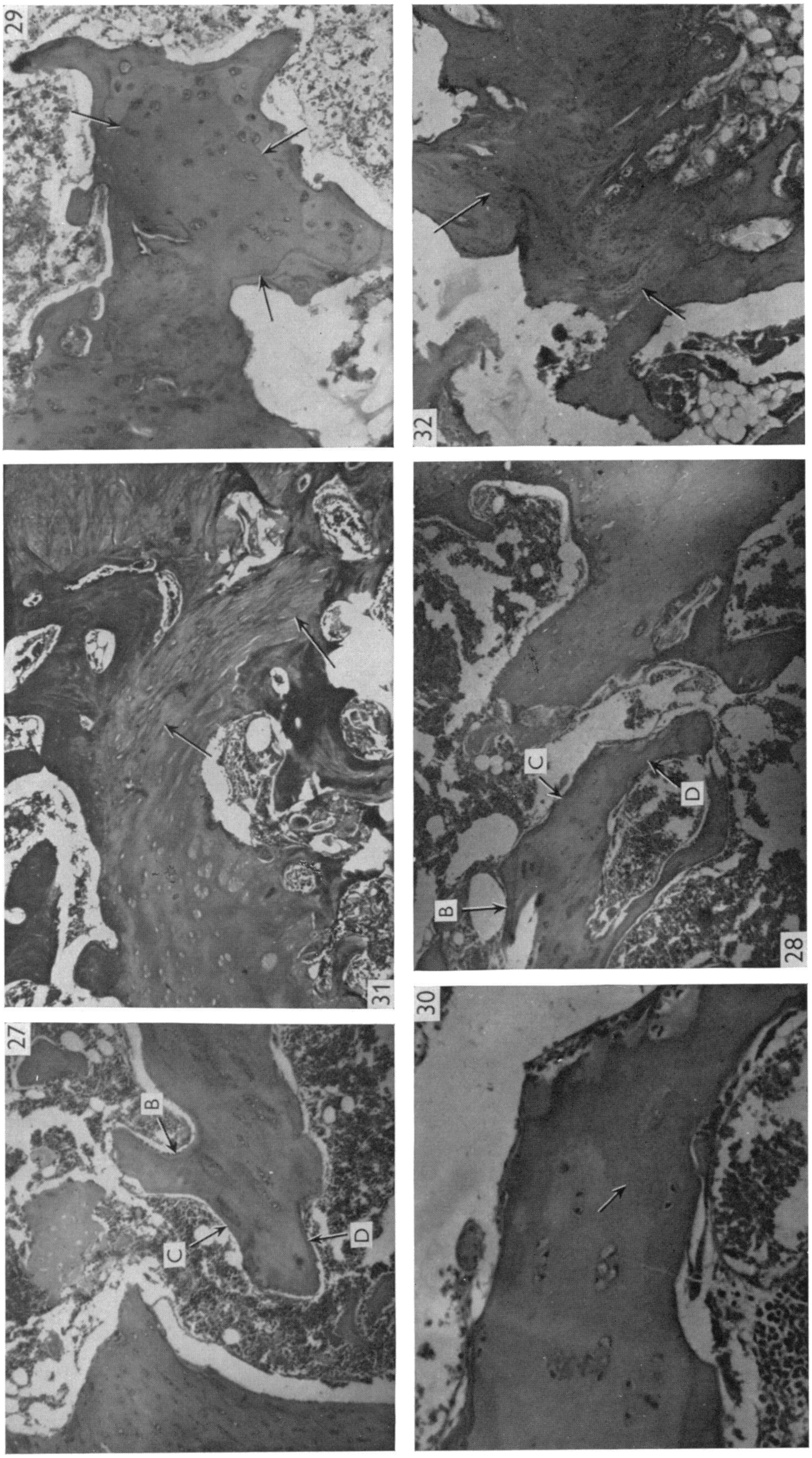
Fig. 25. Tuberosity of calcaneum uniting near plantar margin.

and joined the basal bony plate of the epiphysis to the closing plate of the diaphysis. Next to the capping plates there was a zone of mineralized cartilage, usually separated by a tide-line from the hyaline cartilage (Fig. 29). The advancing margin of mineralization could, however, be granular (Fig. 30). Often neocartilage was found near, or formed the actual margin of, the perforation (Figs. 31, 32).

Expansion of the perforation

In the radial head the original perforation was evidently enlarged by erosion of its margins and at the same time the plate was thinned (Figs. 23, 33). The lamellar bone of the epiphyseal and diaphyseal plates was incomplete so that the marrow could erode the underlying mineralized cartilage and the margin itself was exposed to erosion (Fig. 35). The area of union could be irregular and small islands of cartilage were found separated from the main body in some sections, but the area appeared single. Similar expansions of a single perforation were seen in the olecranon and anterior inferior spine of the ileum. In the medial epicondyle of the

Fig. 26. Proximal end of humerus in early union. Details of cartilage in Figs. 20 and 21, of perforation margin in Fig. 32.



Figs. 27–32. Early perforations of epiphyseal plates. All H. & E.

Fig. 27. Marrow-filled perforation in radial head. Arrows to basal bony plate of epiphysis (*B*), capping plate (*C*) and diaphyseal plate (*D*). ×50.

Fig. 28. Another radius, arrows as in Fig. 27. ×39.

Fig. 29. Margin of perforation in olecranon. Arrows to tide-line demarcating mineralized from hyaline cartilage. ×50.

Fig. 30. Detail of Fig. 28. Arrow to granular mineralization. ×186.

Fig. 31. Perforation in medial epicondyle of humerus. Arrows to neocartilage. ×39

Fig. 32. Margin of perforation in humeral head. Arrows to neocartilage. ×39.

Fig. 33. Radius in late union, the cartilaginous plate thinned and, for the most part, removed. Detail in Fig. 35.

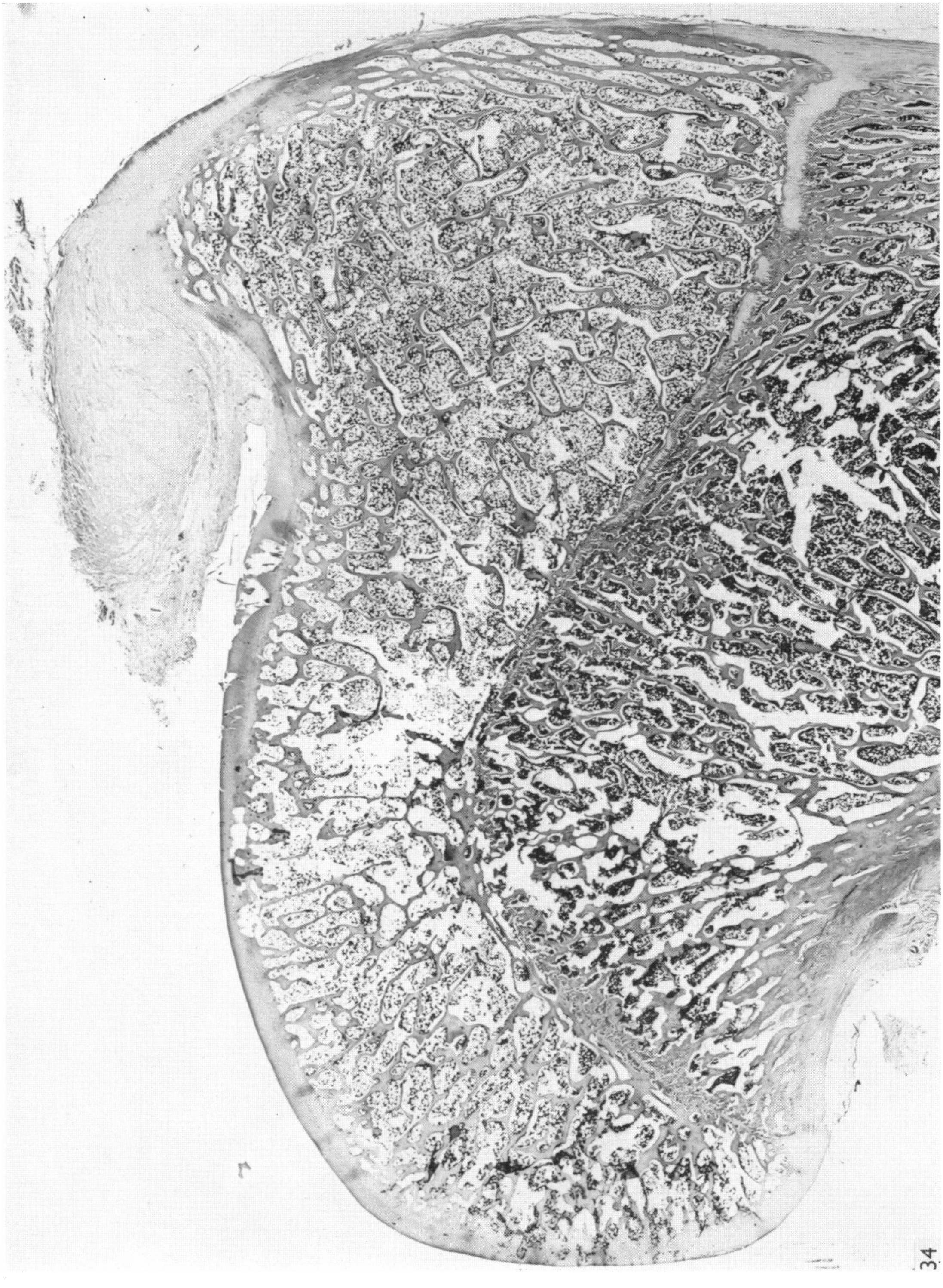
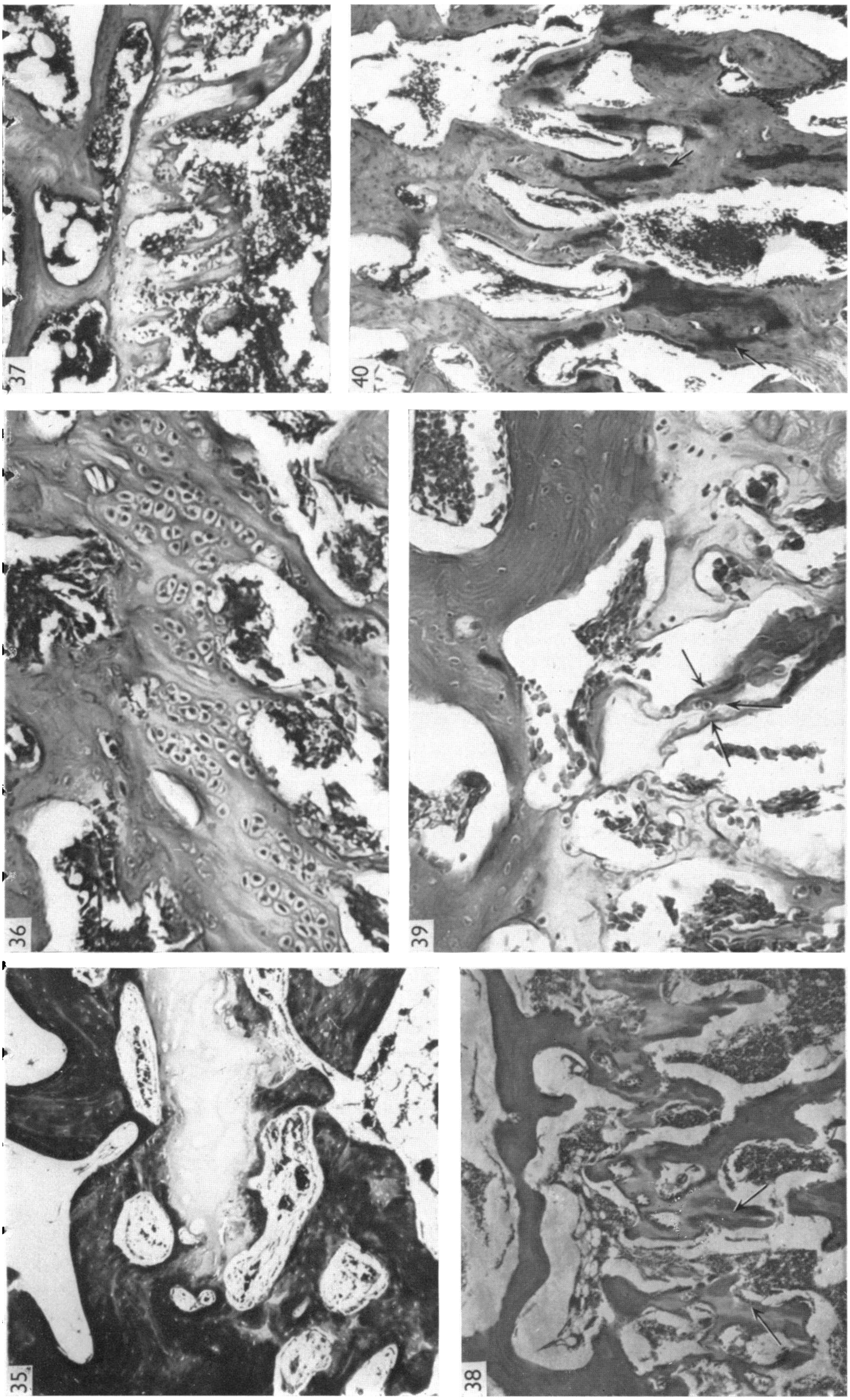


Fig. 34. Head and greater tuberosity of humerus uniting by multiple perforations. Dog of 334 days. Details of epiphyseal plate in Figs. 36, 37; of residual cartilage in Figs. 43, 44.



Figs. 35–40. Union by single and multiple perforations.

Fig. 35. Margin of expanding perforation in a human radial head. Heidenhain's Azan. ×43.

Fig. 36. Well-preserved cartilage columns in uniting humeral head of dog, as Fig. 34. P.T.A.H. ×163.

Fig. 37, Material as Fig. 36, cartilage thinned. ×65.

Fig. 38. Multiple perforations in head of tibia. Dog of 293 days. Arrows to primary trabeculae. P.T.A.H. ×37.

Fig. 39. Material as Fig. 38. Arrows to 3 layers of a primary trabecula. ×157.

Fig. 40. United distal tibial epiphysis. Arrows to cartilage remnants in trabeculae. Dog, 293 days. H. & E. ×51.

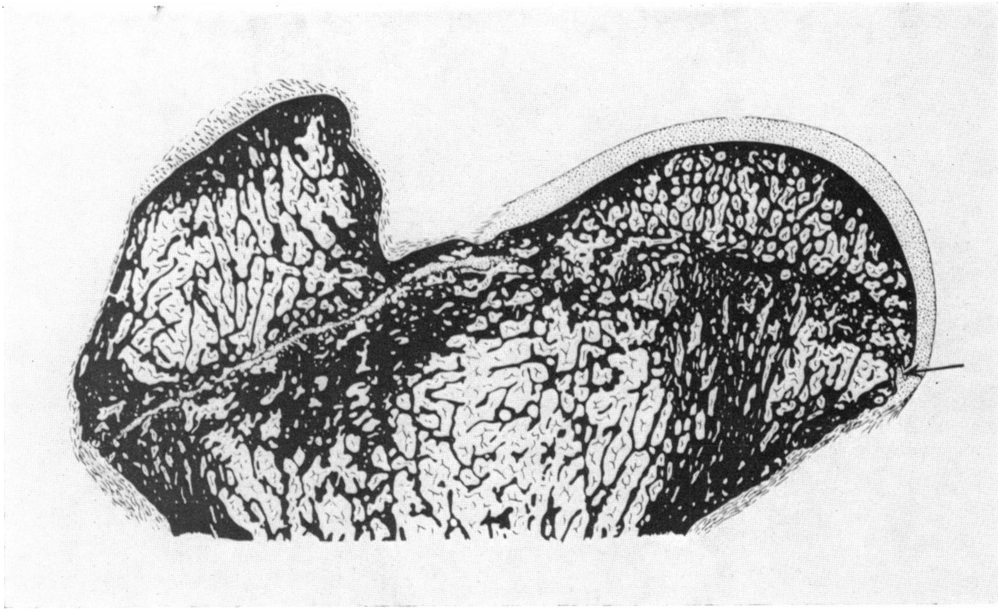


Fig. 41. Femur of dog of 293 days. Head nearing complete union with scar formation, greater trochanter less advanced. Arrow to residual cartilaginous tongue. Detail in Fig. 45.

humerus there could be secondary perforations, but the cartilage structure was as in the radius.

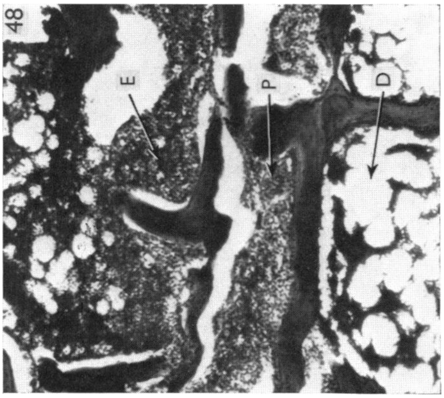
The cartilage with its enclosing bony plates was removed cleanly, leaving no scar. The process continued so that the cartilage was reduced to a narrow shelf projecting into the bone and this was soon cleared away, leaving no evidence of the site of union.

Union by multiple perforations

In a dog's humerus uniting at the proximal end by multiple perforations the cartilage plate was still relatively thick where it supported the greater tuberosity (Fig. 34). Though all the small cells of the resting zone of the cartilage near the epiphysis had been used up, or eroded away, and erosion appeared active on the diaphyseal surface also, the columns themselves were in good condition and their cells were well preserved (Fig. 36). Marrow sprouts had spread up the columns to their tips (Fig. 37) and had laid down bone, forming primary trabeculae, but the sprouts were still cut off from the epiphyseal marrow by a thin continuous layer of cartilage with scattered cells, backed by a discontinuous basal epiphyseal plate.

The tips of the sprouts had broken through to join the epiphyseal marrow, usually that underlying a former basal plate of the epiphysis (Figs. 38, 39). The remnants of the cartilage served as a scaffolding for a series of somewhat irregular primary trabeculae. Even when the basal plate was destroyed, a zone of persistent cartilage in the trabeculae often indicated a site of union (Fig. 40). Such unions by multiple perforations were found in progress at both ends of the humerus and femur, and at the proximal end of the tibia and distal end of the radius in dogs. They were not seen in man, probably because of the lack of suitable material.

Fig. 42. Nearly complete union of distal humeral epiphysis in a dog of unknown age. Arrow to residual cartilage.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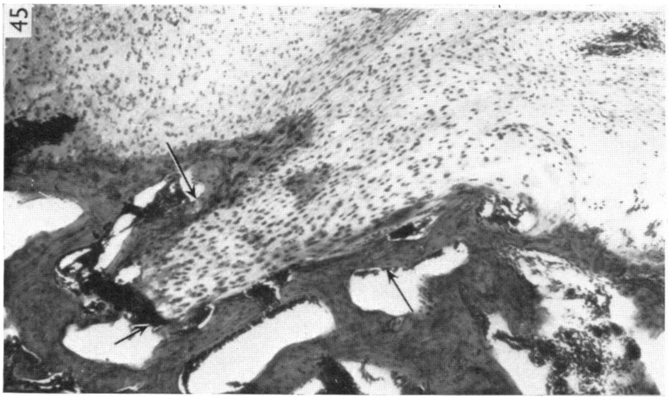
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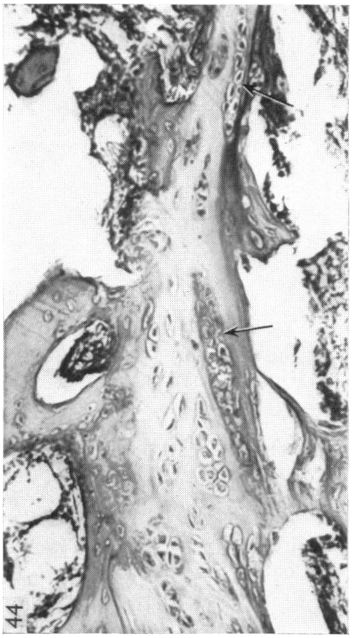
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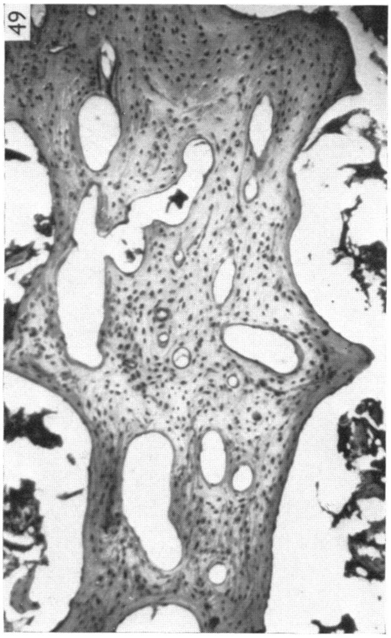
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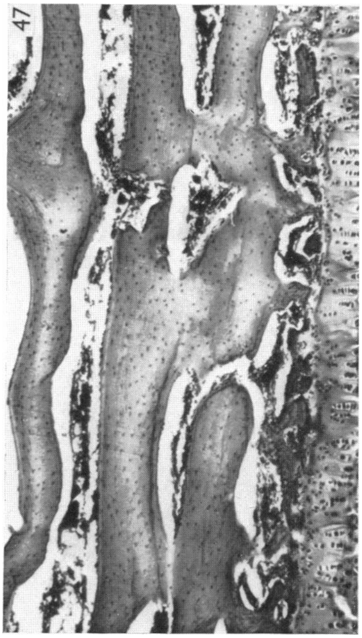
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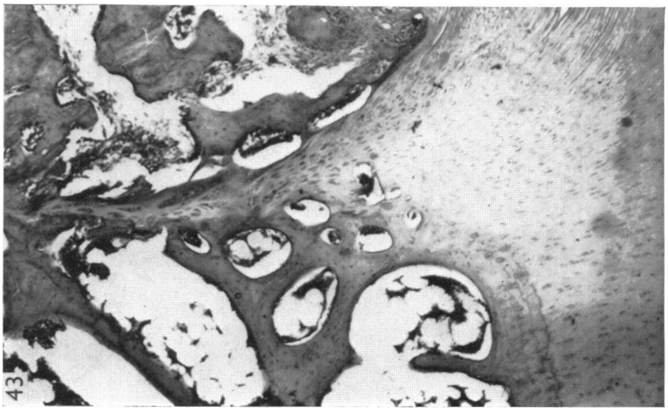
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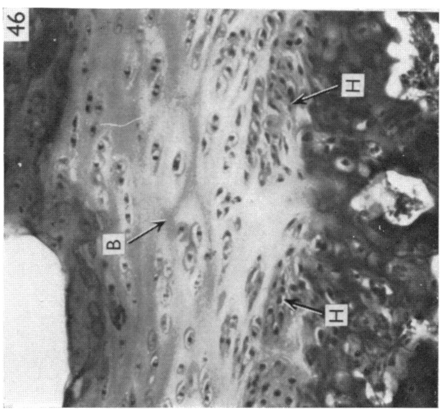
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Residual cartilage

When the cartilage was removed by a single expanding perforation beginning on one margin of the epiphyseal plate the (temporary) remnants of the plate came to be opposite the site of first perforation, e.g. in the radius on the ulnar side (Fig. 33). Here it formed a more or less elongated wedge based on the perichondrium and outlined by discontinuous bony epiphyseal, diaphyseal and capping plates. In union by multiple perforations similar residual cartilage could be found, particularly where the epiphysis overhung the shaft, as at the head of the femur or tibia and distal end of the humerus in the dog (Figs. 41, 42).

The matrix of the residual cartilage remained largely hyaline, while the cells could be flattened and the cartilage columns drawn out in the plane of the tongue, not vertical to it as are the columns of younger epiphyseal cartilage (Figs. 43–45). A similar drawing-out was found between the attachments of the head and great trochanter of a dog's femur (Fig. 46), the young columns and elongated basophilic network of the hyaline cartilage lying across the femur while the mature columns lay parallel to its axis.

Epiphyseal scars

Before union there was a basal plate of epiphyseal bone on the growth cartilage, and several parallel plates could be laid down on its receding surface (Fig. 47). In union by multiple perforation, remnants at least of these plates were retained. They could be recognized by their shape and texture and their identity confirmed by textural variations in the epiphyseal and diaphyseal marrows which persisted long after union (Fig. 48). The plates formed the bases for the scars found in mature bones (Fig. 49). In union by single perforation in man the basal plates were destroyed and scars were not found. In the dog the epiphyses of the fibular and metacarpal heads united early and again there were no scars.

Figs. 43–49. Residual cartilage and epiphyseal scars.

Fig. 43. Residual cartilage at humeral head. Dog of 334 days, detail of Fig. 34. P.T.A.H. × 48.

Fig. 44. As Fig. 43. Arrows to cartilage columns. × 145.

Fig. 45. Residual cartilage at femoral head, detail of Fig. 41. Arrows to bony epiphyseal, diaphyseal and capping plates. H. & E. × 48.

Fig. 46. Epiphyseal plate between head and greater trochanter, detail of Fig. 41. Arrows to basophilic network (*B*) and horizontal cartilage columns (*H*). H. & E. × 140.

Fig. 47. Multiple basal plates of un-united distal radial epiphysis. Dog of unknown age. H. & E. × 48.

Fig. 48. Distal humeral epiphysis of dog of unknown age. Detail of Fig. 42. Arrows to epiphyseal marrow (*E*), marrow replacing epiphyseal plate (*P*) and diaphyseal marrow (*D*). P.T.A.H. × 58.

Fig. 49. Epiphyseal scar from fully united head of human humerus. H. & E. × 37.

DISCUSSION

Cartilage recruitment

In a pig femur, Krompecher (1937) figured a 'granulation tissue' between the epiphyseal marrow and the growth cartilage and suggested that new cartilage cells were being formed in this tissue. Irving (1964) illustrated what may be a similar arrangement in a rat, but did not comment on it. Haines & Mohiuddin (1960) described the development of considerable masses of neocartilage in the humeral head of a healthy young man who died by drowning. The process is here confirmed for other bones. At a much earlier stage of development, new cartilage is injected into the interior of the old by chondrification of the connective tissue of the cartilage canals (Haines, 1974), but these canals disappear long before union. It appears that, although cartilage cells normally divide to form packets and columns (Dodds, 1930), no reserves are left, so that if new cartilage cells are needed they must be differentiated from the cells of other tissues, e.g. perichondrium, cartilage canals or bone marrow, as available. This possibility of recruitment disposes of the otherwise attractive suggestion that epiphyses unite automatically when the supplies of reserve cells in their growth cartilage are used up.

Epiphyseal and diaphyseal plates

Hasselwander (1910), and later radiologists, noted the presence of bony epiphyseal and diaphyseal plates on either side of the growth cartilage (Hasselwander's 'corticalis' of Stadium 1; Hellman, 1928, stage B; Todd, 1930, stage 3). These appeared as dense parallel lines in radiographs. Sidhom & Derry (1931) figured a macerated radius with the head removed to show the two plates and Smith (1962*a*, *b*) showed similar plates from a human tibia and femur and an ox femur. Sections showed each plate to be made partly of epiphyseal or diaphyseal lamellar bone and partly of the peculiar type of mineralized cartilage derived from the growth plate, but these were not distinguishable from one another in radiographs. Indeed they may not be easily distinguishable in sections and Ring (1955) described the basal plate of the distal ulnar epiphysis as a 'plate of bone' though his figure shows that it consisted mainly of mineralized cartilage with a conspicuous tide-line.

The scarcity of signs of erosion on the epiphyseal surface of the growth plate, as compared with their abundance at the diaphyseal surface, has often been noted. But Siegling (1941) goes too far in stating that 'the epiphyseal side . . . shows no signs of activity'. His own photograph shows two small areas of erosion between the bone and the cartilage and such areas can always be found. The tide-lines afford ample evidence of calcification. Fawns & Landells (1953) describe them in the growth cartilage as representing 'the most recently calcified border of this calcified zone, a transition stage with, on one side, cartilage that has passed through it, and on the other, ordinary hyaline cartilage that will shortly become calcified'. The calcified tissue differs from the calcified cartilage of the primary trabeculae in having an acidophilic, instead of a strongly basophilic, matrix; in enclosing apparently healthy cartilage cells, neither hypertrophied nor moribund; and in being bounded by a tide-line or, more rarely, by a granular margin. Lassila (1928) described the tissue in the metatarsal of a calf before union as having the appearance of bone but with cartilage cells in it; and Dawson (1929) spoke of 'chondro-osseous metaplasia' in the rat, with the cartilage cells of the epiphyseal plate 'assuming characteristics of osteoblasts'. It evidently belongs to the set of metaplastic bone tissues formed by the mineralization of various dense tissues, e.g. tendons, ligaments, dense fibrous tissues, cartilages (Keen & Wainwright, 1958; Haines & Mohiuddin, 1968; Hall, 1972). It differs, however, from other types of metaplastic bone in forming little or no part of the adult skeleton.

Early union

Hasselwander (1910), Hellman (1928) and Moss & Noback (1958) found union beginning near the *centre* of the epiphyseal plate in the metatarsals, metacarpals and phalanges, and it has usually been assumed that central union was the rule. Thus Dawson (1925), finding early union at the distal end of the humerus near the periphery of the growth cartilage ('rather than at its center as is usually the case') believed it atypical. The sections presented here confirm the conclusion of Haines, Mohiuddin, Okpa & Viega-Pires (1967), based on dry specimens, that *peripheral* union is *normal* in mammals. In the dog they found union of the olecranon first at the margin further from the olecranon; in Fig. 5C it is at the margin nearer the olecranon, but in both species the perforation is single.

Since invasion of the growth plate is preceded by mineralization the first union of the hard tissues of the shaft and epiphysis must be by metaplastic bone alone, without lamellar bone or marrow. In mammals this stage has not been seen and is probably very transient, but it is known in lizards (Haines, 1941, 'cocalcification' in *Pseudocordylus*; 1969, in *Agama*) and Lassila (1928) found patches of calcified tissue among the perforations in the calf. Again, the continuity of the metaplastic tissue between the shaft and epiphysis in early union in man suggests that this tissue makes the first union.

At the upper end of the tibia and head of the femur Haines *et al.* (1967) found union beginning in regions which Smith (1962*b*) had shown to be fibrous or fibrocartilaginous rather than cartilaginous in structure, but no such localizing determinant could be found in other bones. The frequent association of perforations with showers of neocartilage and the susceptibility of the neocartilage to precocious calcification suggest a possible causal relationship. Dawson (1925) noted thinnings in the cartilage of the rat radius associated with fibrillation of the matrix, and this again may have been due to neocartilage formation.

The Dawson and the Lassila types of union

Union in the radial head of man is characterized by (i) the coating of both surfaces of the cartilaginous epiphyseal plate with lamellar and metaplastic bone, forming the basal bony plates of the epiphysis and diaphysis respectively, (ii) the destruction of the cartilage by a single perforation which begins peripherally and spreads to involve its whole width, (iii) the preservation of the cellular arrangement of the cartilage, including its columns, more or less intact until destruction and (iv) the clean removal of the plate with its associated bony sheets, leaving no scar. In the rat Dawson (1925) found union near the olecranon fossa of the humerus and

Becks *et al.* (1948) found, at 35 days in a late stage of union, that 'remodelling has obliterated any scar marking the former position of the main cartilage plate'. The processes are clearly similar in the two situations.

In the dog, union at the upper end of the femur is characterized by (i) the formation of a relatively strong and continuous basal plate on the epiphyseal surface of the cartilage, but absence or poor development of a diaphyseal plate, (ii) extreme thinning of the plate by sprouts from the diaphyseal marrow, which erode the columns, (iii) multiple perforations scattered over a wide area and (iv) long persistence of trabecular thickenings, giving a bony scar. Lassila (1928) found similar features in the metatarsal head of the calf.

Cheselden (1733) figured epiphyseal scars ('the place in which there is usually only dense substance without spongy cells' at 'the joining of the epiphysis') in the proximal end of the humerus and both ends of the femur; Cope (1920) added the proximal end of the tibia. All these had multiple perforations in the dog. In the forearm bones Cope found no scars, nor were any visible in the sections. Multiple perforations and scars seemed to occur together in the larger and later uniting epiphyses but to be absent from the smaller and earlier uniting ones.

The two types of union described by Dawson and Lassila are inconstant in distribution in different species. Thus, whereas in the dog and man the metatarsals unite in the Dawson way, in the calf they follow the Lassila. Again, the main epiphysis at the distal end of the humerus follows the Dawson course in the rat and man and the Lassila in the dog. It is possible that all the epiphyses of the relatively small early mammals united by the Dawson mechanism, but in later forms some of the epiphyses (the larger and later uniting) have adopted the Lassila type.

Delay in cartilage removal where the epiphyseal plate becomes continuous with the periosteum or perichondrium is responsible for the bony notches often seen radiologically in late stages of union. But it is difficult to account for the peculiar horizontal position of the cell columns in this cartilage, for the arrangement does not correspond to any of the patterns discussed by Kember (1973). It would appear that the margin of the eipiphysis is moving, relatively to the shaft, towards the axis of the bone, but the process is not understood.

Stages of union

Hasselwander (1910) in his classic account of union, based on dry bones and radiographs of the metatarsals and phalanges, described a preparatory phase, three stages of union and a stage following union. Omitting details applicable only to those bones his stages were:

(1) Diaphyseal and epiphyseal plates formed, but still separated by a continuous cartilaginous epiphyseal plate.

(2) Epiphysis and diaphysis fused over a limited area only, elsewhere the cartilage narrowed.

(3) Area of union more extensive, but becoming difficult to analyse by radiography.

(4) Cartilage reduced to remnants occupying notches in the bone.

(5) Cartilage gone and bony trabeculae in complete continuity.

Todd's (1930) account, based on Hellman's (1928) study of the hand, has similar stages. Modern radiological texts give details by which skeletal maturity can be assessed with some accuracy, but add little to our knowledge of the actual process of union (Greulich & Pyle, 1959, for man; Smith & Allcock, 1960, for the dog).

For the *radius*, the bone which is best known, the description of the stages can now be amplified as follows:

(1) Formation of epiphyseal plate of partly lamellar and partly *metaplastic* bone.

(2) Formation of similar diaphyseal plate (completing Hasselwander's stage 1).

(3) Fusion of the metaplastic tissue over a limited area near the margin of the plate (a stage not yet actually seen).

(4) Limited continuity of lamellar bone and marrow between the epiphysis and shaft (Hasselwander's stage 2). The cartilage narrowed by metaplastic change, but only slowly eroded at its surfaces.

(5) The original perforation of the epiphyseal plate expanded by erosion of the plate margin rather than by destruction from either surface (Hasselwander's stage 3), best illustrated by the Baghdad radius (Haines & Mohiuddin, 1959). New bony trabeculae formed as the cartilage is calcified and removed with the bony plates on its surface, leaving no scar, as seen in the dry Lagos radius (Haines *et al.* 1967, Fig. 28).

(6) and (7) As in Hasselwander's stages 4 and 5.

In other bones, early union may be by calcification of fibrous tissue or fibro-cartilage, and spread of union may be much more complex, with multiple perforations, cartilage destruction mainly from its surfaces, and scar formation; but not enough is known of any individual bone, human or otherwise, to give the stages with any assurance.

SUMMARY

Epiphyses of man and dog in various stages of union are described.

As union approaches, new cartilage is added to the epiphyseal surface of the cartilaginous epiphyseal plate by chondrification of the epiphyseal marrow.

Before and during early union the cellular arrangement of the cartilaginous epiphyseal plate is well preserved, with good cartilage columns.

Mineralization of the cartilage, demarcated by tide-lines, spreads from both surfaces, engulfing the cartilage columns. The first union of an epiphysis is by such mineralized tissue, a form of *metaplastic* bone.

In the smaller and earlier-uniting epiphyses, the mineralized cartilage and the sheets of lamellar bone that cover its surfaces are first removed in one restricted area and replaced by new bone and marrow. The original perforation is later enlarged until all the cartilage is destroyed and union is complete, leaving no scar.

In the larger and later-uniting epiphyses there are multiple perforations in the epiphyseal plate and remnants of epiphyseal bone often persist as an epiphyseal scar.

In both types of union remnants of the peripheral parts of the plates may be found for a while with the cartilage columns set at right angles to the axis of the bone

as a whole, an unexplained peculiarity. At full union all such 'residual' cartilage is destroyed.

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